ADAPTIVE TURBO DECISION FEEDBACK EQUALIZATION METHOD AND DEVICE

FIELD OF THE INVENTION

The present invention generally relates to the field of communication systems. More specifically, the invention relates to turbo decision-feedback equalization techniques implemented in a cellular system operating with a multi-path channel.

BACKGROUND OF THE INVENTION

The capacity of a cellular system operating with a multi-path channel can be limited by a demodulator's ability to mitigate the degradations of the received signal due to the multi-path channel. One receiver known in the art for receiving coded transmissions over a multi-path channel is a maximum likelihood sequence estimator ("MLSE") that operates to jointly demodulate the channel and the error correction code. However, the complexity of an MLSE is proportional to P^{L+K}, where P is the number of points in a signal constellation, K is the number of stages in a convolutional code shift register, and L is the number of symbol spaced taps of the multi-path channel. Such complexity impedes an implementation of the MLSE into a cellular system.

Another known receiver for receiving coded transmissions over a multi-path channel is a turbo decision-feedback equalizer ("TDFE") having feed-forward filters and feedback filters that are based upon an estimation of the multi-path channel. While the complexity of the TDFE does not impede the implementation of the TDFE into a cellular system, a problem with the TDFE is the computation of the filters assumes perfect feedback that is not attained in practice.

Therefore, there is a need for an adaptive TDFE. The present invention addresses this need.

SUMMARY OF THE INVENTION

One form of the invention is a method for decoding a packet transmitted over a channel with the packet including a plurality of samples. First, a first set of soft estimates of a plurality of bits is generated based upon a computation of a first feed-forward filter and a first feedback filter as a function of an estimate of the channel. Second, a second set of soft estimates of the plurality of bits is generated based upon a computation of a second feed-forward filter and a second feedback filter as a function of a first set of soft symbol estimates.

A second form of the invention is a device decoding a packet transmitted over a channel with the packet including a plurality of samples. The device includes means for generating a first set of soft estimates of a plurality of bits based upon a computation of a first feed-forward filter and a first feedback filter as a function of an estimate of the channel, and means for generating a second set of soft estimates of the plurality of bits based upon a computation of a second feed-forward filter and a second feedback filter as a function of a first set of soft symbol estimates.

A third form of the present invention is a computer readable medium storing a computer program comprising computer readable code for generating a first set of soft estimates of a plurality of bits based upon a computation of a first feed-forward filter and a first feedback filter as a function of an estimate of the channel, and computer readable code for generating a second set of soft estimates of the plurality of bits based upon a computation of a second feed-forward filter and a second feedback filter as a function of a first set of soft symbol estimates.

The foregoing and other features and advantages of the invention will become further apparent from the following detailed description of the presently preferred embodiment, read in conjunction with the accompanying drawings. The detailed description and drawings are merely illustrative of the invention rather than limiting, the scope of the invention being defined by the appended claims and equivalents thereof.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a block diagram of one embodiment of an adaptive turbo decision feedback equalizer for receiving a packet over a channel in accordance with the present invention;

FIG. 2 is a flowchart illustrating one embodiment of a decision feedback equalization method for generating soft estimates of the bits as known in the art; and

FIG. 3 is a flowchart illustrating one embodiment of an adaptive decision feedback equalization method for generating soft and hard estimates of the bits in accordance with the present invention.

DETAILED DESCRIPTION OF THE PRESENTLY PREFERRED EMBODIMENTS

FIG. 1 illustrates an adaptive turbo decision-feedback equalizer 10 ("adaptive TDFE **10**") in accordance with one embodiment of the present invention. From the subsequent description herein of the adaptive TDFE **10**, those having ordinary skill in the art will appreciate an employment of the adaptive TDFE **10** into a receiver whereby a transmitter transmits a packet including a M Q-ary modulated data symbols and training symbols containing bits, and the adaptive TDFE 10 receives a packet $\mathbf{y}$ including samples $\mathbf{y}(i)$ corresponding to the data symbols and training symbols. In one embodiment, the transmitted packet contains 8-Phase Shift Keying (8-PSK) symbols wherein samples $\mathbf{y}(i)$ are represented by the following equation [1]:

$$\mathbf{y}(i) = \mathbf{H}\mathbf{s}(i) + \mathbf{n}(i) \qquad [1]$$

where the vector of received samples $\mathbf{y}(i)$ in the packet $\mathbf{y}$ is given by the following equation [2]:

$$\mathbf{y}(i) = \begin{bmatrix} y_{i+\delta-1} \\ y_{i+\delta-2} \\ \vdots \\ y_{i+\delta-N_f} \end{bmatrix}, \qquad [2]$$

the Toeplitz channel impulse response matrix $\mathbf{H}$ of dimensions N_f x (N_f + L-1) is given by the following equation [3]:

$$\mathbf{H} = \begin{bmatrix} h_0 & \cdots & h_{L-1} & 0 & \cdots & \cdots & 0 \\ 0 & h_0 & \cdots & h_{L-1} & & & \vdots \\ \vdots & & \ddots & & \ddots & & \vdots \\ 0 & \cdots & \cdots & \cdots & h_0 & \cdots & h_{L-1} \end{bmatrix} \qquad [3]$$

and, the transmitted symbol vector $\mathbf{s}(i)$ is defined in accordance with the following equation [4]:

$$\mathbf{s}(i) = \begin{bmatrix} s_{i+\delta-1} \\ s_{i+\delta-2} \\ \vdots \\ s_i \\ \vdots \\ s_{i+\delta-N_f-L-1} \end{bmatrix} \qquad [4]$$

In the equations [1]-[4], $\mathbf{s}(i)$ represents three coded bits $\{d_k(s(i)), k=1,2,3\}$; $\mathbf{n}(i)$ is a vector of noise samples; N_f is the length of a feed-forward filter **12**; and δ is a delay for optimizing the adaptive TDFE **10**.

In response to a reception of the packet $\mathbf{y}$, the adaptive TDFE **10** executes a flowchart **30** as illustrated in the **FIG. 2** and a flowchart **50** as illustrated in the **FIG. 3**. The flowchart **30** is representative of a decision feedback equalization method for generating a soft estimate of bits within the transmitted packet, and the flowchart **50** is representative of an adaptive decision feedback equalization method for generating soft estimates and hard estimates of the bits within the transmitted packet. The various components of the adaptive TDFE **10** will now be described herein in the context of a sequential execution of the flowchart **30** and the flowchart **50**.

Referring to **FIGS. 1** and **2**, the adaptive TDFE **10** has a first component stage for executing the flowchart **30**. This first component stage includes a channel estimator **11**, a feed-forward filter **12** ("$f^{(1)}$ filter **12**"), an adder **13**, a soft estimate module **14**, and a feedback filter **15** ("$b^{(1)}$ filter **15**") constituting a decision feedback equalizer ("DFE"). The first component stage further includes a switch **16**, a buffer **17**, an *a priori* probability module **18** ("*a priori* module **18**"), a de-interleaver **19**, and a Map decoder **20**. During a block **S32** of the flowchart **30**, the channel estimator **11** estimates the channel coefficients. In one embodiment, the channel estimator **11** estimates the channel coefficients in accordance with the following equations [5] and [6]:

$$\left[\hat{h}_0,\hat{h}_1,\ldots\hat{h}_{L-1}\right]^T = \arg\min_{\mathbf{h}}\left\|\mathbf{y}_T-\mathbf{Th}\right\|^2 = (\mathbf{T}^H\mathbf{T})^{-1}\mathbf{T}^H\mathbf{y}_T \qquad [5]$$

$$\hat{\sigma}_n^2 = \frac{1}{\mathbf{T}}\left\|\mathbf{y}_{\mathrm{T}}-\mathbf{T}\hat{\mathbf{h}}\right\|^2 \qquad [6]$$

where $\mathbf{y}_{\mathrm{T}}$ is the T x 1 vector of the received training symbols represented by the following equation [7]:

$$\mathbf{y}_T = \begin{bmatrix} y_L \\ y_{L+1} \\ \vdots \\ y_T \end{bmatrix} \qquad [7]$$

and the matrix T is a Toeplitz matrix of transmitted training symbols s_i that is given by the following equation [8]:

$$\mathbf{T} = \begin{bmatrix} s_L & s_{L-1} & \cdots & s_1 \\ \vdots & \vdots & \vdots & \vdots \\ s_T & s_{T-1} & \cdots & s_{T-L} \end{bmatrix} \qquad [8]$$

Upon completion of the block **S32**, the adaptive TDFE **10** proceeds to a block **S34** to compute the $f^{(1)}$ filter **12** and the $b^{(1)}$ filter **15** as a function of the channel coefficients. In one embodiment, the $f^{(1)}$ filter **12** and the $b^{(1)}$ filter **15** are computed in accordance with the following equations [9] and [10]:

$$\mathbf{f}^{(1)} = \left(\hat{\mathbf{H}}_{1\delta}\hat{\mathbf{H}}_{1\delta}^{H} + \hat{\sigma}_n^2\mathbf{I}\right)^{-1}\hat{\mathbf{h}}_{\delta}$$

[9]

$$\mathbf{b}^{(1)}(k) = \begin{cases} 0 \quad , & k = 1:\delta-1 \\ \left(\mathbf{f}^{(1)}\right)^{H}\hat{\mathbf{h}}_k \ , & k = \delta : N_f + L - 1 \end{cases}$$

[10]

where the $\mathbf{H}_{1:\delta}$ represents columns in 1 through δ of the estimated channel matrix $\mathbf{H}$; $\hat{\mathbf{h}}_k$ represents the k^{th} column of the estimated channel matrix $\mathbf{H}$; and $\hat{\mathbf{h}}_{\delta}$ represents the δ^{th} column of the estimated channel matrix $\mathbf{H}$.

Upon completion of the block **S34**, the adaptive TDFE **10** proceeds to a block **S36** wherein the packet $\mathbf{y}$ and the soft estimates $s^{(1)}(i)$ are filtered through the $f^{(1)}$ filter **12** and the $b^{(1)}$ filter **15**, respectively, to obtain DFE outputs $\mathbf{z}^{(1)}(i)$. In one embodiment, the adder **13** provides the DFE outputs $\mathbf{z}^{(1)}(i)$ in accordance with the following equation [11]:

$$z^{(1)}(i) = \left(\mathbf{f}^{(1)}\right)^{H}\mathbf{y}(i) + \left(\mathbf{b}^{(1)}\right)^{H}\hat{\mathbf{s}}^{(1)}(i)$$

[11]

where the soft estimate module **14** estimates the soft feedback symbols $\hat{\mathbf{s}}^{(1)}(i)$ in accordance with the following equations [12]-[17]:

$$\hat{s}^{(1)}(i) \equiv E\left[z^{(1)}(i) \middle| s(i)\right] = \sum_{k=0}^{7} P\left(z^{(1)}(i) \middle| s(i) = e^{j\frac{\pi k}{4}} \right) \cdot e^{j\frac{\pi k}{4}}$$

[12]

$$\mathrm{P}\left(z^{(1)}(i)\middle|s(i)=e^{j\frac{m\pi}{4}}\right)=\prod_{k=1}^{3}\mathrm{P}\left(z^{(1)}(i)\middle|d_k(s(i))=d_k(e^{j\frac{m\pi}{4}})\right),\quad \text{for } m=0,1,\ldots 7$$

[13]

$$\mathrm{P}\left(z^{(1)}(i)\middle|d_k(s(i))=\pm 1\right)=\sum_{s\in\Omega^{\pm}}k_s\frac{1}{\sqrt{2\pi\sigma^2}}\exp\left(\frac{-\left|z^{(1)}(i)-\mu s\right|^2}{\sigma^2}\right),$$

[14]

$$k_s=\frac{\mathrm{P}(\textbf{Transmitted Symbol}=\mathbf{s})}{\sum_{s'\in\Omega^{\pm}}\mathrm{P}(\textbf{Transmitted Symbol}=\mathbf{s'})}$$

[15]

$$\mathrm{E}\left[z^{(1)}(i)\middle|s(i)\right]=\mu s(i)=\left|\left(\mathbf{f}^{(1)}\right)^H\mathbf{h}_\delta\right|s(i)$$

[16]

$$\mathrm{Var}\left[z^{(1)}(i)\middle|s(i)\right]=\sigma^2=\sigma_n^2\left\|\mathbf{f}^{(1)}\right\|^2+\left\|\left(\mathbf{f}^{(1)}\right)^H\mathbf{H}_{1\delta}\right\|^2$$

[17]

where $\{d_k(s(i)),\ k=1,2,3\}$ are the bits which correspond to $\mathbf{s}^{(1)}(\mathrm{i})$; $\Omega^{\pm}$ is the set of symbols which correspond to the value of $d_k(s(i))$; and k_s is a normalization factor.

Upon completion of the block **S36**, the adaptive TDFE **10** proceeds to a block **S38** of the flowchart **30** to set switch **16** to provide the output $\mathbf{z}^{(1)}(\mathrm{i})$ to the buffer **17**. In response thereto, the buffer **17** stores the DFE outputs $\mathbf{z}^{(1)}(\mathrm{i})$.

Upon completion of the block **S38**, the adaptive TDFE **10** proceeds to a block **S40** of the flowchart **30** to generate *a priori* probabilities $\mathbf{P\{z^{(n)}(i)|d_k(s(i))\}}$. In one embodiment, the priori module **18** generates the *a priori* probabilities $\mathbf{P\{z^{(n)}(i)|d_k(s(i))\}}$. in accordance with the following equations [18]-[21]

$$\mu_m = \frac{1}{M+T} \sum_{i=0}^{M+I-1} \left| (\hat{s}^{(n)}(i))^* z^{(n)}(i) \right| \qquad [18]$$

$$\sigma_m^2 = \frac{1}{M+T} \sum_{i=0}^{M+T-1} \left| (\hat{s}^{(n)}(i))^* z^{(n)}(i) - \mu_m \right|^2 \qquad [19]$$

$$\mathrm{P}\left(z^{(1)}(i) \middle| d_k(s(i)) = \pm 1\right) = \sum_{s \in \Omega^{\pm}} k_s \frac{1}{\sqrt{2\pi\sigma_m^2}} \exp\left(\frac{-\left| z^{(1)}(i) - \mu_m s \right|^2}{\sigma_m^2} \right), \qquad [20]$$

$$k_s = \frac{\mathrm{P}(\textbf{Transmitted Symbol} = \mathbf{s})}{\sum_{s' \in \Omega^{\pm}} \mathrm{P}(\textbf{Transmitted Symbol} = \mathbf{s'})} \qquad [21]$$

Upon completion of block **S40**, the adaptive TDFE **10** proceeds to a block **S42** of the flowchart **30** wherein the de-interleaver **19** conventionally de-interleaves the *a priori* probabilities $P\{z^{(n)}(i)|d_k(s(i))\}$and feeds them to the MAP decoder **20**. In response thereto, during a block **S44** of the flowchart **30**, the MAP decoder **20** generates a soft estimate of the bits in the form of *a posteriori* probabilities $\mathbf{P\{d_k(s(i))|z^{(1)}\}}$. In one embodiment, the MAP decoder **20** implements a conventional Bahl-Coch-Jelinek-Raviv ("BCJR") algorithm to generate *a posteriori* probabilities $\mathbf{P\{d_k(s(i))|z^{(1)}\}}$.

The flowchart **30** is terminated upon completion of block **S44**.

Referring to **FIGS. 1** and **3**, the adaptive TDFE **10** has a second component stage for executing the flowchart **50** immediately upon termination of the flowchart **30**. The second component stage includes the switch **16**, the buffer **17**, the *a priori* module **18**, the de-interleaver **19**, the MAP decoder **20**, a switch **21**, and an interleaver **22**. The second component stage further includes a soft estimates module **23**, a filter coefficients module **24**, a

feedback filter **25** ("$b^{(n)}$ filter **25**"), a feed-forward filter **26** ("$f^{(n)}$ filter **26**"), and an adder **27** constituting an adaptive decision feedback equalizer.

During a block **S52** of the flowchart **50**, the switch **21** is set to provide the *a posteriori* probabilities $\mathbf{P\{d_k(s(i))|z^{(n)}\}}$ to the interleaver **22**. In response thereto, the interleaver **22** conventionally interleaves the *a posteriori* probabilities $\mathbf{P\{d_k(s(i))|z^{(n)}\}}$. Upon completion of the block **S52**, the adaptive TDFE **10** proceeds to a block **S54** of the flowchart **50** wherein the soft estimates module **23** computes soft estimates of the transmitted symbols $\mathbf{s}^{(n)}(\mathrm{i})$ in accordance with the following equations [22] and [23]:

$$\hat{s}^{(n)}(i) \equiv E\left[s(i)\middle|z^{(n)}\right] = \sum_{k=0}^{7} P\left(s(i) = e^{j\frac{\pi k}{4}}\middle|z^{(n)}\right) \cdot e^{j\frac{\pi k}{4}} \tag{22}$$

$$\mathrm{P}\left(s(i) = e^{j\frac{m\pi}{4}}\middle|\mathbf{z}^{(n)}\right) = \prod_{k=1}^{3} \mathrm{P}\left(d_k(s(i)) = d_k(e^{j\frac{m\pi}{4}})\middle|z^{(n)}(i)\right), \quad \text{for } m = 0,1,\ldots 7 \tag{23}$$

Upon completion of block **S54**, the adaptive TDFE **10** proceeds to block **S56** of the flowchart **50** wherein the filter coefficients module **24** computes the $b^{(n)}$ filter **25** and the $f^{(n)}$ filter **26** in accordance with the following equations [24]-[27]:

$$\mathbf{x} = \begin{bmatrix} \mathbf{y}(i) \\ \hat{\mathbf{s}}_{\delta}^{(n)}(i) \end{bmatrix} \qquad [24]$$

$$\begin{bmatrix} \mathbf{f}^{(n)} \\ \mathbf{b}^{(n)} \end{bmatrix} = \mathbf{R}_{\mathbf{xx}}^{-1}\mathbf{R}_{\mathbf{x}\hat{s}^{(n)}}, \quad \text{where} \qquad [25]$$

$$\mathbf{R}_{\mathbf{xx}} = \sum_{i=0}^{M-1} \mathbf{x}(i)\mathbf{x}^{H}(i) \qquad [26]$$

$$\mathbf{R}_{\mathbf{x}\hat{s}^{(n)}} = \sum_{i=0}^{M-1} \mathbf{x}(i)\left(\hat{s}^{(n)}(i)\right)^{*} \qquad [27]$$

where $\hat{\mathbf{s}}_{\delta}^{(n)}(i)$ is the vector $\hat{\mathbf{s}}^{(n)}(i)$ whose δ^{th} element has been set to zero.

Upon completion of the block **S56**, the adaptive TDFE **10** proceeds to a block **S58** of the flowchart **50** wherein the packet $\mathbf{y}$ and the soft symbol estimates $\mathbf{s}^{(n)}(i)$ are filtered through the $f^{(n)}$ filter **26** and the $b^{(n)}$ filter **25**, respectively, to obtain DFE outputs $\mathbf{z}^{(n)}(i)$. In one embodiment, the adder **27** computes the DFE outputs $\mathbf{z}^{(n)}(i)$ in accordance with the following equation [28]:

$$z^{(n)}(i) = \left(\mathbf{f}^{(n)}\right)^{H} \mathbf{y}(i) + \left(\mathbf{b}^{(n)}\right)^{H} \hat{\mathbf{s}}^{(n)}(i) \qquad [28]$$

Upon completion of the block **S58**, the adaptive TDFE **10** proceeds to a block **S60** of the flowchart **50** to set switch **16** to provide the DFE outputs $\mathbf{z}^{(n)}(\mathbf{i})$ to the buffer **17**. In response thereto, the buffer **17** stores the DFE outputs $\mathbf{z}^{(n)}(\mathbf{i})$.

Upon completion of the block **S60**, the adaptive TDFE **10** proceeds to a block **S62** of the flowchart **50** to generate *a priori* probabilities $\mathbf{P\{z^{(n)}(i)|d_k(s(i))\}}$. In one embodiment, the priori module **18** generates the *a priori* probabilities $\mathbf{P\{z^{(n)}(i)|d_k(s(i))\}}$ in accordance with the following equations [29]-[31]

$$\mu_m = \frac{1}{M+T}\sum_{i=0}^{M+T-1}\left|(\hat{s}^{(n)}(i))^* z^{(n)}(i)\right| \qquad [29]$$

$$\sigma_m^2 = \frac{1}{M+T}\sum_{i=0}^{M+T-1}\left|(\hat{s}^{(n)}(i))^* z^{(n)}(i) - \mu_m\right|^2 \qquad [30]$$

$$\mathrm{P}\left(z^{(1)}(i)\middle| d(i,j)\right) = \pm 1 \cong \sum_{S\in\Omega}\frac{1}{\sqrt{2\pi\sigma_m^2}}\exp\left(\frac{-\left|z^{(1)}(i) - \mu_m s\right|^2}{\sigma_m^2}\right) \qquad [31]$$

Upon completion of block **S62**, the adaptive TDFE **10** proceeds to a block **S64** of the flowchart **50** wherein the de-interleaver **19** conventionally de-interleaves *a priori* probabilities $\mathbf{P\{z^{(n)}(i)|d_k(s(i))\}}$and feeds them to the MAP decoder **20**. In response thereto, during a block **S66** of the flowchart **50**, the MAP decoder **20** generates either a soft estimate of the bits in the form of *a posteriori* probabilities $\mathbf{P(d_k(s(i))|z^{(n)})}$. In one embodiment, the Map decoder **20** implements a BCJR algorithm to generate *a posteriori* probabilities $\mathbf{P\{d_k(s(i)|z^{(n)}\}}$.

The flowchart **50** is immediately terminatec upon a completion of the block **S66** when only one iteration of blocks **S52-S66** is contemplated. With one completed iteration, the switch **21** is set to provide the *a posteriori* probabilities $\mathbf{P(d_k(s(i))|z^{(n)})}$ as hard estimates $\mathbf{\hat{b}(i)}$ of the bits. Thus, the soft symbol estimates $\mathbf{s}^{(n)}(i)$, the $b^{(n)}$ filter **25** and the $f^{(n)}$ filter **26** are computed only once when only one iteration of blocks **S52-S66** is contemplated.

Preferably, the flowchart **50** is terminated after plurality of n iterations (e.g., 4 iterations) of the blocks **S52-S66** as shown in **FIG. 3**. As such, the switch **21** is set to provide the *a posteriori* probabilities $P\{d_k(s(i)|z^{(n)}\}$ to the interleaver **22** upon completion of each intermediate iteration of the blocks **S52-S66**, and the switch **21** is set to provide the *a posteriori* probabilities $P\{d_k(s(i)|z^{(n)}\}$ as hard estimates $\hat{b}(i)$ of the bits upon completion of the final iteration of the blocks **S52-S66**. Those having ordinary skill in the art will appreciate the repeated computations of the soft symbol estimates $s^{(n)}(i)$, the $b^{(n)}$ filter **25** and the $f^{(n)}$ filter **26** during the multiple iterations of the blocks **S52-S66** in effect produce separate and distinct soft symbol estimates $s^{(n)}(i)$, $b^{(n)}$ filters **25** and $f^{(n)}$ filters **26** for each iteration.

The illustrated embodiments of the present invention may be implemented in hardware, software stored on a computer readable medium, or combinations of hardware and software. The present invention may be embodied in other specific forms without departing from its spirit or essential characteristics. The described embodiments are to be considered in all respects only as illustrative and not restrictive. The scope of the invention is, therefore, indicated by the appended claims rather than by the foregoing description. All changes that come within the meaning and range of equivalency of the claims are to be embraced within their scope.